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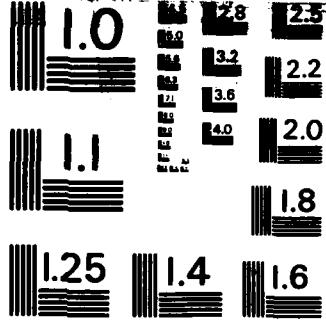
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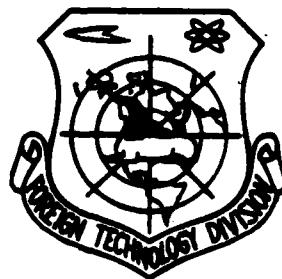


MASS SPECTROMETERS FOR STUDYING THE IONIC AND NEUTRAL  
COMPOSITION OF THE UPPER LAYERS OF THE ATMOSPHERE

by

M. D. Shutov

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О о	О о	O, o	Ю ю	Ю ю	Yu, yu
П п	П п	P, p	Я я	Я я	Ya, ya

\*ye initially, after vowels, and after ъ, ъ; e elsewhere.  
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	$\sech^{-1}$
cosec	csc	csch	csch	arc csch	$\csch^{-1}$

Russian	English
rot	curl
lg	log

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## **MASS SPECTROMETERS FOR STUDYING THE IONIC AND NEUTRAL COMPOSITION OF THE UPPER LAYERS OF THE ATMOSPHERE**

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### **1. INTRODUCTION**

The investigation of the ionic and neutral composition of the upper layers of the atmosphere and outer space is of great interest for solving theoretical and applied problems of astrophysics, geophysics, space biology, and other closely-tied areas of science. The study of the upper layers of the atmosphere is of practical significance for launching rockets and artificial satellites, for which the nature of movement depends on the structure and composition of the atmosphere. The study of the chemical composition of the ionosphere, the degree of ionization of the upper layers of the atmosphere at different latitudes and different times of day, and the dependence of ionization on the action of ultraviolet and corpuscular radiation is necessary in order to study the processes of the propagation of radio waves, and to explain the chemical and photochemical reactions which cause the ionosphere to exist.

One of the most modern methods of studying the composition of the upper atmosphere should be considered to be the mass-spectral method [24], which is a direct method and is especially valuable at great

altitudes. Actually, while the composition of the neutral gases at relatively low altitudes (up to 800-100 km) can also be determined by other methods, e.g., by sampling the air in balloons and analyzing the chemical composition after they fall to the Earth, at present, the only method for analyzing the composition of the ionizing gases in the upper layers of the atmosphere is the mass-spectrometric method.

Mass spectrometers are launched into the upper layers of the atmosphere and outer space on rockets and artificial satellites. The results of the analysis are transmitted to the ground over a radio-telemetry system.

Mass spectral studies of the composition of the upper layers of the Earth's atmosphere and outer space consist of measuring the partial pressures of the components of the gas mixture in a deep vacuum. Therefore, the absence of an evacuation system is a typical characteristic of the mass spectrometers for these studies.

When selecting the type of mass spectrometer for studying the upper layers of the atmosphere, it is necessary to consider a number of specific requirements which are imposed on the instruments in this case. The main ones are: small weight and power consumption, automatic operation, ability to withstand mechanical overloads, high sensitivity, ability to work in a wide ambient temperature range, operational reliability, and also small dimensions, determined not only by the limitations caused by the dimensions of the rockets and satellites, but also by the fact that the length of the free path of the molecules must be much greater than the dimensions of the instrument's sensor, etc.

Mass spectrometers with magnetless dynamic analyzers have been used to solve this problem: radiofrequency, time-of-flight and quadrupole.

## 2. RADIOFREQUENCY MASS SPECTROMETERS

The radiofrequency mass spectrometer is a dynamic system with the

separation of the positive ions of the analyzed gases in high-frequency electrical fields [1, 25]. It has been used repeatedly to study the upper layers of the atmosphere. In 1952, Townsend et al. described a radiofrequency mass spectrometer that was used to study the neutral composition of the upper layers of the atmosphere during rocket investigations [2, 3]. Johnson and Meadows used a radiofrequency mass spectrometer to study the composition of ionizing gases [4]. The radiofrequency mass spectrometer RMS-1, developed by Istomin, was installed on the third Soviet artificial Earth satellite [5].

A series of small radiofrequency mass spectrometers types MKh6401, MKh6403, MKh6405 and MKh6407P [6-9] has been developed in the USSR in recent years to study the upper layers of the atmosphere and outer space. All these types of instruments consist of one or two radiofrequency analyzers and an electronic module. The first type MKh6401 models had relatively low sensitivity and were primarily intended for analyzing the neutral composition of gases. The subsequent models make it possible to analyze both the neutral, and the ionic composition. In the latter case, the ion source is disconnected and the positive ions of the gas being investigated are drawn into the analyzer directly from the atmosphere.

The radiofrequency mass spectrometers of the indicated models have been successfully used to study outer space, in particular, on "Elektron" satellites [10].

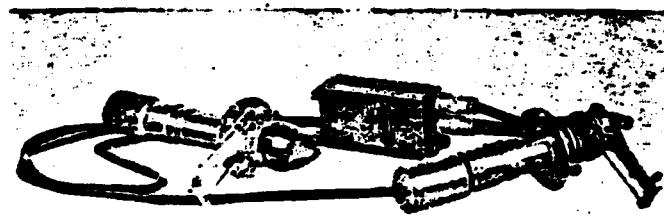


Fig. 1. External view of mass spectrometer MKh6407P.

The latest model of radiofrequency mass spectrometer MKh6407P (Fig. 1) is distinguished by a high sensitivity threshold, being around  $3 \cdot 10^{-11}$  torr<sup>1</sup> ( $5 \cdot 10^{-10}$  torr in instrument MKh6401). Figure 2 shows a block diagram of instrument MKh6407P.

<sup>1</sup>1 torr = 1 mm Hg. The name "torr" (from Torricelli) has not been officially established, but is widely used in vacuum technology. (Editor's note).

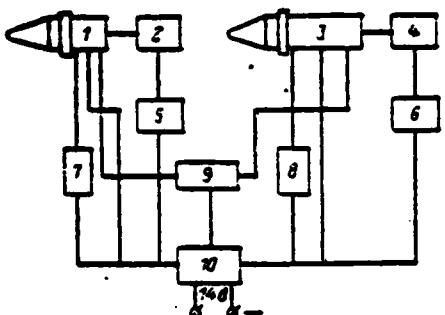


Fig. 2. Block diagram of mass spectrometer MKh6407P.

- 1 - mass analyzer of light masses;
- 3 - mass analyzer of heavy masses;
- 2, 4 - electromagnetic stage;
- 5, 6 - ion current amplifier;
- 7, 8 - high-frequency generator;
- 9 - mass spectrum scanning circuit;
- 10 - instrument supply circuit.

The assembly of mass spectrometer MKh6407P consists of two three-stage mass analyzers with separating devices (see below) for injecting the analyzed atmosphere into the instrument, an electronic module, and two electrometric heads. The presence of two mass analyzers with resolution of 5 and 20 in the assembly makes it possible to simultaneously conduct the analysis in the range of light (1-4) and heavy (12-50) masses.

The analyzers are of the same design, differing only in the length

of the housing because drift space with a different length is used. Figure 3 shows an overall view of the analyzer. It is a cylindrical housing made of stainless steel, which contains three grating stages made of gratings with high optical transparency, an ion source, cylinders which limit the drift space, a collector, and a number of other structural units which provide for assembling and fastening the electrodes of the analyzer and insulate them from the housing.

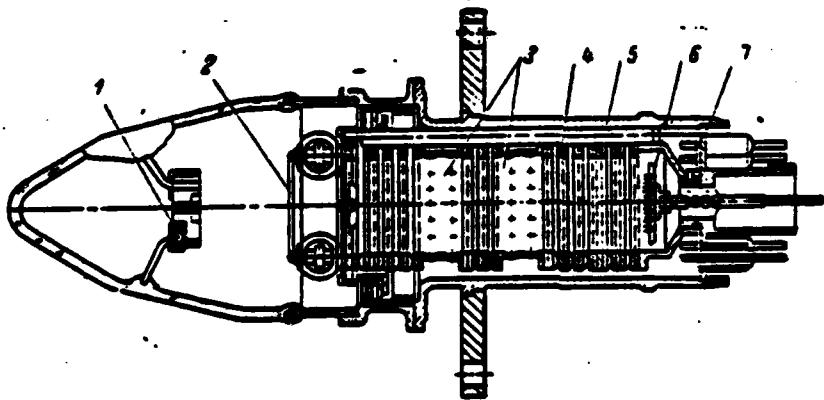


Fig. 3. Overall view of mass analyzer.

- 1 - gas absorber;
- 2 - ion source;
- 3 - drifts;
- 4 - grating;
- 5 - housing;
- 6 - collector;
- 7 - base.

The analyzer circuit is connected to a base welded to the analyzer. The front part of the analyzer, which houses the getter, is made in the form of a glass tube. A nondispersing titanium-zirconium getter that does not absorb inert gases is used as the getter. This is a necessary condition, since the analyzers are filled with a control mixture ( $H_2$ , He, Ne, Ar) when they are made.

The analyzer (for cases of analyzing a molecular composition) is outfitted with a high-efficiency economical ion source, whose design makes it possible to remove the glowing cathode from the zone of the passage of ions or molecules, which considerably decreases the background from gas liberation of the cathode. The reflector in the ion source is under a small negative potential relative to the cathode, which provides the maximum passage of the electrodes emitted by the cathode into the ionization chamber.

Mass spectrometer MKh6507P has the capability of conducting an analysis at a reduced sensitivity, which is necessary when analyzing the composition of gases at relatively high pressures.

Under operating conditions, the analyzers are connected with the atmosphere by opening the glass connecting pipe with a special separating device consisting of a plate, a spring, and an arming wire. The separating device operates when the arming wire is ignited by the current.

The electronic module of mass spectrometer MKh6407P consists of the double ion current amplifier, mass spectrum scanning circuits, and instrument supply circuits. The double amplifier consists of two electrometric amplifiers, and it measures the ion currents in the collector circuits of the analyzers [11]. The first stage of the ion current analyzer leads to the electrometric stage (the electrometric head). The head also contains the high-frequency oscillator, which increases the ion energy in the three-grating stages of the analyzers. The electrometric head is structurally connected with the analyzer. The instrument's supply circuit includes a power converter with a voltage stabilization system. The electronic module is connected with the analyzers, the telemetry system, the program unit, and the power source by shielded cables.

The circuits of the electronic module are mainly constructed with semiconductor elements by printed wiring, which made it possible to reduce the module's weight to 500 g, with the entire assembly weighing 2.5 kg. The instrument has low power consumption, not exceeding 5 W

when a neutral composition is being analyzed, and 3 W - when analyzing an ion composition. The instrument can be supplied from any direct-current source with voltage of  $14\pm 2$  V. The instrument's design provides for automatically changing the spectral scanning rate, the possibility of switching the sensitivity and operating mode (the analysis of an ionic or neutral composition), etc. Instrument MKh6407P is equipped with a special monitor which makes it possible to test the main parameters of the instrument on the ground, including observing the mass spectrum on a CRT.

### 3. TIME-OF-FLIGHT MASS SPECTROMETERS

The development of mass-spectral studies of the upper layers of the atmosphere and outer space imposes more and more rigid requirements on the equipment, with one of these requirements being higher speed. The following circumstances have determined the need for increasing the speed of the instruments. The movement of the rocket or satellite on which the mass spectrometer is installed means that the position of the sampling point changes continuously. For example, when the instrument carrier moves at a speed of 8 km/s, the mass spectrum taken for 3 s refers to a layer 24 km thick. It should also be noted that when the rocket rotates (precesses), the angle between the normal to the inlet hole of the instrument and the direction of the incoming gas flow changes continuously. As we know, this distorts the mass spectrum and makes it more difficult to process the observation results.

The speed was increased by using a time-of-flight mass spectrometer.

The operating principle of the analyzer of the time-of-flight mass spectrometer is based on the differences in the time taken to pass through a space that is free from the action of appreciable electrical and magnetic fields (the drift space) by ions with different values of the mass-to-charge ratio [12-16, 24]. Report [17] contains the first mention of the creation of a small time-of-flight mass spectrometer for studying the upper layers of the atmosphere. The instrument was small, but it was not fast. The six selected components of the mass

spectrum were determined in 2 min. each. The mass spectrometer worked on a frequency of 10 kHz at a single mass spectrum duration of 40  $\mu$ s.

Report [18] gives data on the operation of the small time-of-flight mass spectrum made by Bendix (USA) that was used on a satellite to measure the N and O concentrations. Report [19] gives the results of measuring the ratio of the concentrations of atomic and molecular oxygen up to an altitude of 200 km obtained using a time-of-flight mass spectrometer.

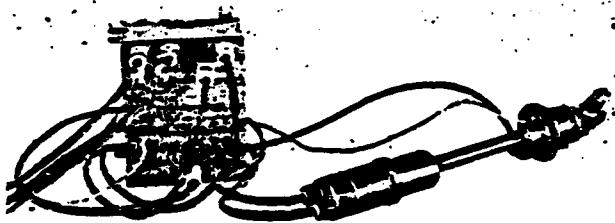


Fig. 4. External view of time-of-flight mass spectrometer MKh5401.

The problem of the expediency of using a time-of-flight mass spectrometer in addition to the equipment available for studying the composition of the upper layers of the atmosphere was also considered in Soviet literature [20]. The first small Soviet time-of-flight mass spectrometer MKh5401 was designed for analyzing the neutral components of the upper atmosphere in the range of 1-100 u. Figure 4 shows an overall view of mass spectrometer MKh5401. The main units of the mass spectrometer are the mass analyzer and the measuring unit. Figure 5 shows a block diagram of instrument MKh5401.

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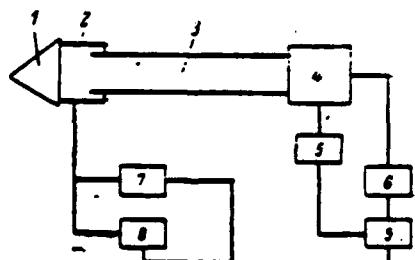


Fig. 5. Block diagram of mass spectrometer MKh5401.

1 - opened device; 2 - ion source; 3 - drift tube; 4 - electron multiplier; 5 - wide-band amplifier; 6 - multiplier supply unit; 7 - pulse generator; 8 - ion source supply unit; 9 - instrument supply unit.

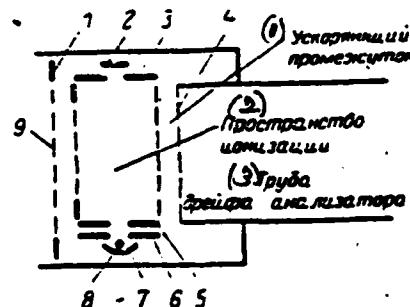


Fig. 6. Diagram of ion source of mass spectrometer MKh5401.

1 - protective grating; 2 - electron collector; 3 - slit in front of collector; 4 - grating of ionization chamber; 5 - electrode; 6 - control electrode; 7 - cathode reflector; 8 - cathode; 9 - ejection grating.  
KEY: (1) Accelerating gap. (2) Ionization space. (3) Analyzer drift tube.

The analyzer is a sealed electronic device which contains a mixture of gases under a pressure of around  $1 \cdot 10^{-5}$  torr. The main elements of the analyzer are the ion source, the drift tube, the secondary electron multiplier, and the opening device.

When the opening device is separated, the ion source (Fig. 6) is connected with the atmosphere under investigation. The molecules of the analyzed mixture enter the ionization space through the protective grating, which is electrically connected with the ejection grating. The ionized particles of the atmosphere do not enter the source because of the deflection field between the protective grating and the housing. The cathode, reflector, control electrode and collector form an electron gun that is triggered by the pulse supplied to the control electrode. An ionizing pulse lasting  $10^{-7}$  s with a slope of the leading front of  $3 \cdot 10^{-8}$  s and an amplitude of up to 60 V is also fed to the control electrode from the generator which is part of the measuring module.

Ion packets with an initial duration of  $10^{-7}$  s are formed in the ionization space with a frequency of 600 Hz (the generator frequency). These packets are ejected into the accelerating gap by the permanent field between the ejection grating and the grating of the ionization chamber. The accelerating voltage was selected as 100 V. The accelerated ions enter the drift tube, and, (after separation), they go to the input of the multiplier, with a multiplication factor of  $10^6$ .

The main elements of the measuring module are the wide-band amplifier, the pulse generator, and the power unit. The generator of the mass spectrometer can operate both in the self-excitation mode, and in the external synchronization mode (both with a frequency of around 600 Hz).

The power unit of the electron multiplier supplies the latter with a voltage of 3 kV at a current load of 600  $\mu$ A. The stability of the rectified voltage is  $\pm 1\%$ . The multiplier of instrument MKh5401 is the diode system of photomultiplier FEU-47, which has ten activated aluminum-magnesium emitters mounted on mica plates.

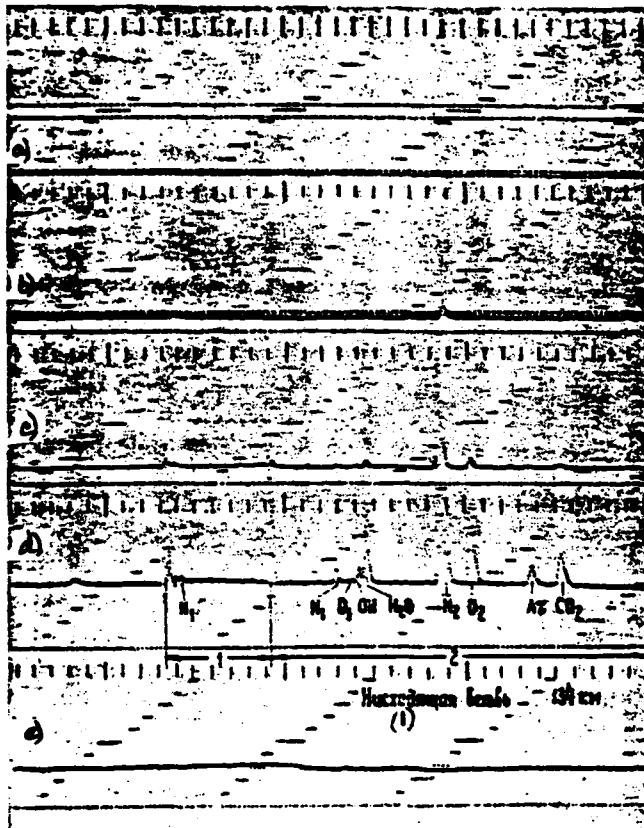


Fig. 7. Mass spectra of neutral composition of upper layers of the Earth's atmosphere transmitted over radio-telemetry system.

a-e - successive sections of diagram strip;

1, 2 - first and second measurement limits with respect to mass numbers.

KEY: (1) Descending branch.

Instrument MKh5401 is equipped with a set of ground testing equipment.

#### 4. QUADRUPOLE MASS SPECTROMETERS

The studies of the composition of the upper layers of the atmosphere conducted using a

quadrupole mass spectrometer [21, 22] are of great interest. The instrument was launched on rockets to an altitude of up to 200 km, and it made it possible to obtain extremely interesting data on the

Table. Characteristics of certain mass spectrometers designed for studying the composition of the upper layers of the atmosphere.

(1) Тип прибора (2) Характеристики	(3) Прибор Тьюсона (США)	PMC-1 (СССР)	MX5401 (СССР)	MX5403 (СССР)	MX5405 (СССР)	MX5407П (СССР)	MX5401 (время- полетная) (СССР)	(5) Квадру- польный (США)	
(6) Радиочастотные									
Диапазон масс, а. е. м. . . . .	5-16	6-16	a) 1-4; б) 12-56	a) 1-4; б) 12-56	a) 1-2; б) 12-36	a) 1-4; б) 12-48	1-100	1-48	
Разрешающая способность . . . . .	25	20	50	50	20	5	16	40	
(7) Вес, кг (без источников питания) . . . . .	6	6	3,3	2,0	2,0	2,5	4,3		
(8) Потребляемая мощность, вт . . . . .	30	25	6,0	4,0	4,0	5	18		
(9) Количество источников питания . . . . .	13	12	1	1	1	1	1		
(10) Время развертки одного масс-спектра, сек . . . . .	2,5	2,5	2,5	2,5	2,5	2,5	1/600	2	
(11) Шаговая чувствительность (по аргону), торр . . . . .	—	—	5·10 <sup>-8</sup>	5·10 <sup>-8</sup>	1·10 <sup>-8</sup>	3·10 <sup>-11</sup>	5·10 <sup>-8</sup>		

KEY: (1) Type of instrument. (2) Characteristics. (3) Townsend instrument (USA).

(4) (time-of-flight) (USSR). (5) Quadrupole (USA). (6) Radio-frequency. (7) Range of masses, u [atomic mass units]. (8) Resolution. (9) Weight, kg (without power source). (10) Power consumed, W. (11) Number of power sources. (12) Scan time of one mass spectrum, s. (13) Sensitivity threshold (for argon), torr.

gaseous composition of the upper layers of the atmosphere. The operating principle of the quadrupole mass analyzer is based on the separation of the ions according to the mass-to-charge ratio in the field of a quadrupole capacitor, to the electrodes of which direct-current and high-frequency voltages are supplied. The absence of a magnet, the relative simplicity of the analyzer, the high ion utilization factor for the ions that enter the analyzer, the possibility of obtaining trapezoidal ion current spikes with low resolution, and also the possibility of obtaining high resolution, led to the creation of a series of mass spectrometers based on this type of mass analyzer. The resolution of the mass spectrometer increases in direct proportion to the analyzed mass. The analyzer operates satisfactorily when the pressure is increased up to  $5 \cdot 10^{-3}$  torr. The quadrupole mass spectrometer has sufficiently high sensitivity. All of these factors make it possible to expect quadrupole mass spectrometers to find further use when studying outer space.

## 5. CONCLUSION

The table gives the characteristics of certain mass spectrometers designed for studying the composition of the upper layers of the atmosphere.

At present, mass spectrometers are used extensively in many experiments on studying the ionic and neutral composition of the upper layers of the atmosphere and outer space that are being conducted by Soviet and foreign scientists. Figure 7 shows a typical mass spectrum obtained in the experiment described in report [23].

The further use of mass spectrometers to study the upper layers of the atmosphere and outer space, as well as the improvement of the equipment, will make it possible to obtain valuable new data on the Earth's atmosphere and outer space.

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